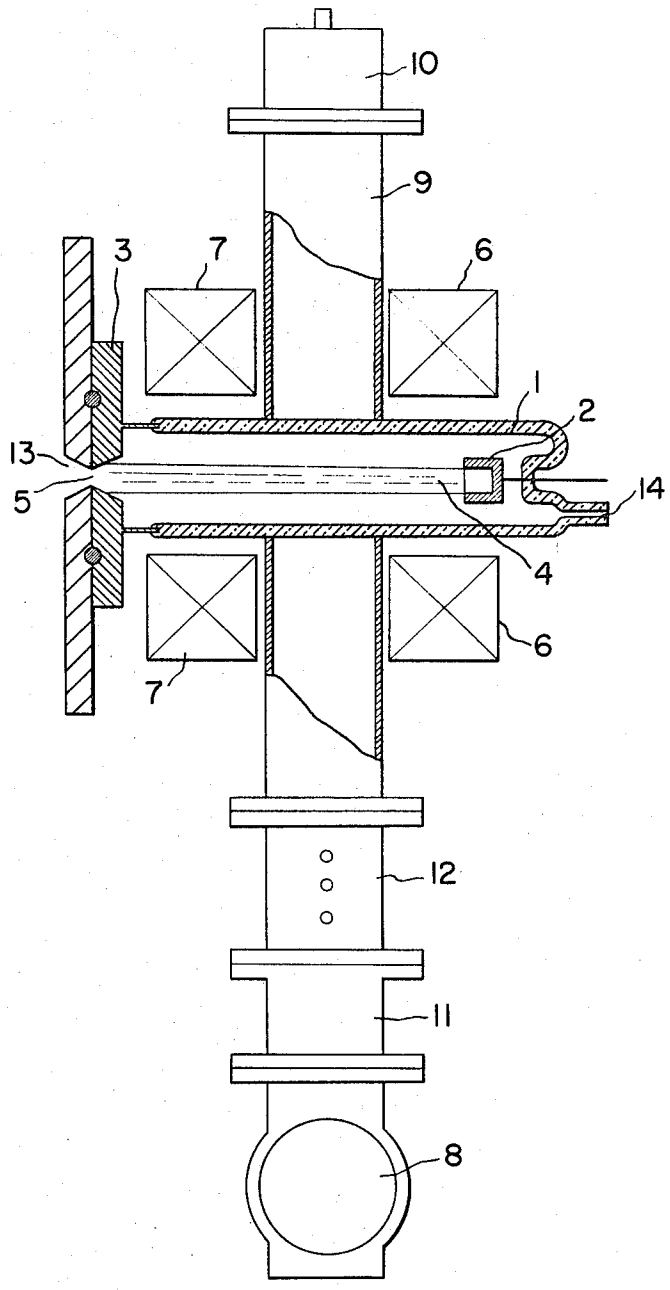
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ELECTRON CYCLOTRON RESONANCE HEATING DEVICE

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ELECTRON CYCLOTRON RESONANCE HEATING DEVICE

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U.S. Cl. 315—39 1 Claim

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ABSTRACT OF THE DISCLOSURE

An electron cyclotron resonance heating device of a type wherein a discharge plasma is generated in the magnetic field along the axial direction, into which a high frequency incident electromagnetic wave is projected perpendicularly with respect to the direction of the magnetic field, thereby causing the electrons in the plasma to absorb the energy of the incident electromagnetic wave, and the electrons in the plasma are further heated to a high temperature so as to cause a light beam of short wavelength, in the far ultraviolet region, to emanate from the plasma.

This application is a continaution-in-part of prior application Ser. No. 252,484 filed on Jan. 18, 1963, now abandoned, in the name of Taro Dodo and Manabu Yamamoto, and entitled Electron Cyclotron Resonance Heating Device.

This invention relates to a novel electron cyclotron resonance heating device for generating far ultraviolet radiation of great importance and value for such work as spectroscopic analysis and research on photochemical reactions.

As is known, the range of light wavelengths from several angstroms to 2000 angstroms is generally referred to as the "far ultraviolet region." Since, in such work as experimental spectroscopic analysis in this wavelength region, vacuum spectrometers are required because of absorption due to air, this region is also known as the "vacuum ultraviolet region." Because the spectra of molecules, atoms, and ions having excitation energies of approximately 6 ev. or more fall within this region, far ultraviolet spectroscopy is indispensable in the study of the molecular structures and electronic states of such molecules, atoms, and ions. Furthermore, since high-temperature plasmas of several tens of thousands of degrees Kelvin emit far ultraviolet light, far ultraviolet spectroscopic technique is considered to be necessary for measurement of high temperature plasmas. This technique is applied also to such observations as those of the sun, stars, and night sky and is useful for attaining knowledge relating to space.

When this technique is further applied to spectroscopic analysis, since the intense spectrum lines of nonmetallic elements are within the far ultraviolet region, the technique is of great importance in the analysis of nonmetallic impurities in the refining processes of steel and other metals. For example, the sensitive lines of such substances as carbon, phosphorus, and sulfur of relatively high composition content in iron and steels are within the far ultraviolet region; accordingly, quality control of even higher precision than that possible heretofore should become possible with progress in techniques in far ultraviolet spectroscopic analysis.

In this far ultraviolet region, however, such difficulties as lowering of transparency and reflection coefficients of

prisms and reflecting mirrors and the lowering of the detector sensitivity are encountered. For this reason, a light source of as high an intensity as available is required. Among the light sources used heretofore, many have been of the type wherein capacitors charged to high voltages of approximately 10,000 volts are discharged in a vacuum, examples of such sources being hot spark devices, sliding spark devices, and the Lyman tube. However, in all of these devices, reproducibility is poor, and the serviceable life is short because of erosion of such parts as electrodes and tube wall. Furthermore, since high voltage is used, these devices have further disadvantages such as the occurrence of discharge between the discharge tube and the spectrometer or the contamination of the spectrometer interior by the spatter of the electrodes and tube wall.

In addition, light sources in which, instead of capacitor discharge, continuous discharge in hydrogen gas or rare gases is utilized have also been used. In the case of many of these light sources, however, the greater part of the radiation is in the visible or ultraviolet region, and the far ultraviolet radiation is weak. The reason for this is that the temperature of the plasma within the discharge tube is low, and intense far ultraviolet rays are not radiated from a plasma of a temperature below 10,000 degrees Kelvin generated by ordinary discharge. The basic reason for this deficiency will now be considered in some detail.

The distribution of atoms or ions in the states of exciting energy under the condition of thermal equilibrium may be expressed by the so-called Boltzmann factor exp. $(-E/kT)$, where E is the excitation energy, k is the Boltzmann constant, and T is temperature (degrees K.). When the abovesaid factor is calculated for excitation energy (approximately 6 ev.) corresponding to a wavelength of 2000 angstroms, the result is approximately 1/1000 for T=10,000 deg. K., approximately 1/30 for T=20,000 deg. K., and approximately 1/10 for T=30,000 deg. K. That is, by increasing the temperature three times, the intensity of light of 2000 angstrom wavelength is increased 100 times. This ratio of intensity increase becomes even greater with shorter wavelengths. Accordingly, in order to cause the radiation of considerably intense far ultraviolet rays from light sources used at present, it is desirable that the temperature be at least 20,000 degrees K. and preferably 30,000 degrees K. or higher.

An important point to be noted here is that, for radiation of far ultraviolet rays, it is not necessary for all of the particles in the plasma to be equally at a temperature of 20,000 to 30,000 degrees K. or higher. The reason for this is that excitation and ionization of gas atoms are accomplished principally by the collision of high velocity electrons with these gas atoms, and, provided that the kinetic energy of the electrons can be increased, the aim of generating far ultraviolet rays is attained. More explicitly, causing the mean kinetic energy possessed by the electrons to increase, that is, in equivalent effect, elevating the electron temperature and preventing unnecessary kinetic energy from being supplied to ions and other gas particles are the fundamental conditions for generating far ultraviolet radiation with high efficiency.

In view of the foregoing considerations, it is an object of the present invention to provide a new electron cyclotron resonance heating device for generating a special high-temperature plasma which, with relatively low power supply, accomplishes generation of the above-mentioned far ultraviolet radiation.

It is a specific object of the invention to provide a device as stated above wherein energy is supplied to only the electrons within the plasma, without heating the ions, and the plasma is heated with extremely high efficiency.

The foregoing objects have been achieved by the present invention, in which the phenomenon of absorption

of electromagnetic radiation by electron cyclotron resonance is utilized. In order to facilitate a clear and full understanding of the principle and nature of the invention, the following analytical description is presented.

A plasma of electron density N (cm.$^{-3}$) existing in a magnetic field of magnetic flux density B (kilogauss) will be considered. The properties of this plasma can be expressed by two representative quantities. The first quantity represents the collective motion of the electrons and is commonly called the plasma oscillation frequency. When denoted by f_p, this quantity is expressed by the following equation:

$$f_p=\frac{1}{2\pi}\left(\frac{4\pi Ne^2}{m}\right)^{1/2}\doteqdot 8{,}900\ \sqrt{N}\ (c/\text{sec.}) \tag{1}$$

where e is electron charge; and m is electron mass. The second important quantity is the gyration frequency produced when the individual electrons become encompassed about the magnetic flux and undergo so-called cyclotron gyration. When denoted by f_c, this quantity is expressed by the following equation:

$$f_c=\frac{1}{2}\pi\cdot\frac{eB}{mc}=2{,}800\ B\ (mc./\text{sec.}) \tag{2}$$

where e represents electron charge; and m is electron mass.

If, into this plasma as described above, an electromagnetic wave of frequency f is projected, the electromagnetic wave will be intensely absorbed by the plasma at a certain frequency and only at this frequency. As is well known, this phenomenon, which has been determined theoretically and confirmed experimentally, is caused by the resonance of the afore-mentioned three frequencies, namely, the characteristic frequencies f_p and f_c of the electrons within the plasma and the frequency f of the incident electromagnetic wave, and is commonly referred to as electron cyclotron resonance absorption. The condition for the occurrence of this resonance when the direction of propagation of the electromagnetic wave is parallel to the magnetic field is that the frequency f be approximately as follows:

$$f=f_c \tag{3}$$

The said condition when the said direction and said magnetic field are mutually perpendicular is that the frequency f be approximately as follows:

$$f=\sqrt{f_p^2+f_c^2} \tag{4}$$

Since this resonance absorption is due to individual or collective motion of the electrons, and the ions of atoms do not participate directly in this resonance absorption, the process of energy transfer from the electromagnetic wave to the electrons is accomplished with extremely high efficiency.

The invention will become more clearly understood by the following detailed description when read in conjunction with the accompanying drawing the single view of which illustrates one embodiment of an electron cyclotron resonance heating device according to the present invention.

Referring to the drawing, the device comprises: a discharge tube made of insulating material such as glass, one end in the axial direction of the tube being connected to a vacuum spectrometer entrance slit **13** through an anode electrode **3** having in its center a slit **5** and the other end being provided with a gas inlet **14** for discharge or ionization gas; a cathode electrode **2** disposed in the said tube in alignment with the axial line of the tube **1**, a D-C current or low-frequency voltage being impressed between the said anode and cathode so as to generate discharge plasma **4** in the axial direction of the tube **1** through a subsidiary discharge such as an arc discharge, etc. being carried out by the electrodes; a pair of coils **6**, **7** which are wound about the tube **1** to generate a magnetic field occurring in the axial direction of the said tube; a magnetron **8** to serve as a high-frequency power source; a rectangular waveguide **9**; a shorting plunger **10**; an isolator **11**; and a three stub matching section **12**. The discharge tube **1** passes through the rectangular waveguide **9** orthogonally, so that any micro-wave which propagates within the said waveguide **9** advances vertically with respect to the strong magnetic field in the axial direction of the tube created by the coils **6** and **7**.

Now, the operation of this device will be described. The discharge tube **1** contains an ionization gas at a low pressure of the order of about 1μ Hg. This ionization gas is exhausted from the slit **5** during operation of the device and the amount of gas decreased for the portion is replenished from the gas inlet **14**. The gas to be used for this purpose can be of any kind in principle, but an inert gas is usually employed. Within this discharge tube containing a sealed-in gas, there is conducted an electric discharge such as, for example, a D-C arc discharge between the anode and the cathode, whereby a discharge plasma **4** is generated. At this time, a strong D-C magnetic field is impressed by the coils **6** and **7** in the direction of the tube axis, i.e., in the flowing direction of the discharge current. Next, the magnetron **8** is actuated to supply a microwave which is propagated in the direction orthogonal to the above-mentioned magnetic field in the axial direction of the discharge tube by means of the rectangular waveguide **9**. This magnetron can be operated either continuously or on repeated pulse. The output of the magnetron can be about 20 kw. peak at the time of pulse operation and about 20 w. in average.

An incident electromagnetic wave is thus supplied from the magnetron **8** to the square or rectangular wave guide **9**. Since the discharge tube **1** is disposed through the side walls of the wave guide **9**, the electromagnetic wave, that is propagated through the wave guide **9**, is projected into the plasma **4** in a direction perpendicular to the magnetic field. Accordingly, the oscillation frequency at which the said electromagnetic wave gives rise to resonance absorption within the plasma **4** is determined from the aforestated Equation 4.

As an example, when the magnetic density B is 3 kilogausses, the cyclotron oscillation frequency is given from Equation 2 as $f_c\simeq 8700$ (mc./sec.). Moreover, when the electron density within the plasma is 10^{11} (cm.$^{-3}$), the plasma oscillation frequency is given by Equation 1 as $f_c\simeq 2800$ (mc./sec.). Accordingly, the resonance frequency is given by Equation 4 as

$$f=\sqrt{f_p^2+f_c^2}\simeq 9100\ (\text{mc./sec.})$$

That is, when a microwave of a frequency of 9100 (mc./sec.) is directed into the plasma **4**, an intense, mutual interference is caused, the microwave power is absorbed by the electrons within the plasma. During this operation, it is possible that some power passes through without being absorbed by the plasma. However, since this power is reflected by one end **10** of the wave guide **9** and is directed again into the plasma, the quantity of ineffective power is extremely small.

It is preferred to use a magnetron for the high frequency power source **8**, and its operation may be either continuous or a repeated-pulse operation.

In the device of this invention of the above-described construction, the electrons within the plasma absorb microwave power, and it is possible to maintain, constantly, electron temperatures of 20,000 to 30,000 degrees K. or higher. From the plasma of such extremely high temperature, light rays in the far ultraviolet region are led out to the outside as a parallel-ray light beam through a passage opening **5** provided in the center of the electrode **3**.

It is to be observed from the foregoing description that the electron cyclotron resonance heating device according to the present invention, differing from a simple plasma generating device of direct-current or low-fre-

quency discharge type, is one in which a high-frequency electromagnetic wave is supplied into a plasma to cause the power of the said electromagnetic wave to be absorbed by the electrons within the plasma, that is, to cause so-called electron cyclotron resonance absorption to take place, and energy is supplied to only the electrons within the plasma, whereby a plasma of extremely high temperature, which has heretofore been unattainable, is generated with extremely high efficiency. Accordingly, the present invention provides a light source for far ultraviolet radiation requiring relatively low power and is particularly applicable to spectroscopic analysis, photochemical reaction, and research on such subjects as the energy levels of atoms.

Although the present invention has been described in conjunction with a preferred embodiment thereof, it is to be understood that modifications as variations may be resorted to therein without departing from the spirit and scope of the invention, as those skilled in the art will readily understand. Such modifications and variations are considered to be within the purview and scope of the invention and appended claims.

What is claimed is:

1. An electron cyclotron resonance heating device which comprises, in combination:

a sealed horizontal discharge tube of insulating material containing a gas at low pressure;

a pair of electrodes disposed at each end of said discharge tube to maintain direct current discharge plasma;

an external coil wound about said tube generating an axial magnetic field in said tube;

a waveguide traversed substantially at right angles by said tube; and

a high-frequency power source connected to said waveguide to supply an electromagnetic wave propagating therethrough and being projected into said plasma in a direction perpendicular to said magnetic field to bring about resonance absorption by its oscillation frequency f, said frequency f satisfying the following relationship

$$f=\sqrt{f_p^2+f_c^2}$$

where f_p is the plasma frequency and f_c is the cyclotron frequency.

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